ALUMINUM WIRE ROPE
POLYETHYLENE SHEATHING FAILURE

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John A. Hiltz

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Approved by: R.M. Morchat _____

Head / Dockyard Laboratory (Atlantic)

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Abstract

The results of an investigation of the cracking of the polyethylene (PE) sheathing on aluminum wire rope used on CF Ships are reported. The cracking had not been observed previously and there was concern that this might be related to a change in material or storage conditions. Thermal analysis techniques, such as differential scanning calorimetry (DSC) and pyrolysis-gas chromatography/mass spectrometry (py-GC/MS) indicated that the failed sheathing was higher density PE than the sheathing that did not crack. Analysis of the fracture surface of the cracked sheathing indicated that it had failed by a brittle slow crack growth mechanism. The failure of the higher density PE was attributed to stresses introduced when the sheathed wire rope was transferred to a reel with a smaller diameter. Although the wire rope with the uncracked sheathing had also been transferred to a reel with a smaller diameter, low density PE is less susceptible to this type of cracking.

Résumé

Présentation des résultats d'une étude sur la fissuration de la gaine de polyéthylène (PE) d'un câble d'aluminium utilisé à bord des navires des Forces canadiennes. La fissuration n'avait pas été observée précédemment et on pensait qu'elle pouvait être liée à changement de condition du matériau ou de l'entreposage. Les techniques d'analyse thermique, comme la calorimétrie à compensation de puissance et la pyrolyse-chromatographie gazeuse/spectrométrie de masse (py-CG/SM) ont indiqué que le PE de la gaine fissurée était d'une densité supérieure à celui de la gaine non fissurée. L'analyse de la surface de fracture de la gaine fissurée a montré que la défaillance avait été causée par un mécanisme de propagation lente de la fissure par fragilisation. La fissuration du PE de densité supérieure a été attribuée à contraintes introduites lorsque le câble a été transféré sur un tambour de plus petit diamètre. Bien que le câble dont la gaine n'était pas fissurée ait aussi été transféré sur un tambour de plus petit diamètre, le PE de densité inférieure est moins sensible à ce type de fissuration.

Executive Summary

DREA Technical Memorandum TM/97/258

Aluminum Wire Rope Polyethylene Sheathing Failure
by John A. Hiltz

The results of an investigation of the cracking of the polyethylene (PE) sheathing on aluminum wire rope used on Canadian Forces Ships are reported. As the cracking had not been observed previously, DMSS 4-3 requested that DREA Dockyard Laboratory (Atlantic) determine why the sheathing was cracking. Discussions indicated that there were samples of wire rope in stores that did not have cracked sheathing.

Thermal analysis techniques, such as differential scanning calorimetry (DSC) and pyrolysis-gas chromatography/mass spectrometry (py-GC/MS) indicated that the failed sheathing was higher density PE than the sheathing that did not crack. Analysis of the fracture surface of the cracked sheathing indicated that it had failed by a brittle slow crack growth mechanism. This failure mode is characterized by failures at loads well below those required for tensile failure.

The failure of the higher density PE was attributed to stresses introduced when the sheathed wire rope was transferred to a reel with a smaller diameter. These introduced stresses on the cable sheathing that lead to the brittle slow crack growth failure. Although the wire rope with the uncracked sheathing had also been transferred to a reel with a smaller diameter, low density PE is less susceptible to this type of cracking.

Two courses of action are recommended to prevent failures of this type. As transferring the wire rope to reels with smaller diameters than those coming from the manufacturer introduces the stresses necessary for the failure, this practice should be stopped. Alternatively, the Life Cycle Material Manager can specify that the sheathing be made from low density polyethylene that is less susceptible to brittle slow crack growth failure.

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Introduction

Polyethylene (PE) is used in a broad range of applications as a result of its low cost, processibility, low density, toughness, and excellent chemical resistance. It is a semicrystalline thermoplastic polymer and contains amorphous (glasslike) and crystalline phases. Polyethylene is produced in a number of grades that are differentiated on the basis of their density. These grades include low density (LD), linear low density (LLD), high density (HD) and high molecular weight high density (HMWHD) polyethylene. The density of a polyethylene sample depends on the degree of crystallinity. The specific gravity of LDPE and LLDPE varies from 0.91 to 0.94, while the specific gravity of HDPE and HMWHDPE varies from 0.94 to 0.965.

The thermal, physical and mechanical properties of the various PEs are dependent on their structure. For instance, LDPEs are less crystalline and have lower flexural moduli (stiffness) than HDPEs. The crystallinity of polyethylenes can vary for a variety of reasons. These include differences in molecular weight, branching in the polymer chain introduced through the use of copolymers, the processing conditions including thermal history (rate of cooling) and application of loads, and cross-linking.

Additives can have a significant effect on the performance and service life of the polymer. A number of additives, including antioxidants, ultraviolet stabilizers, colorants, and agents to promote cross-linking, are used in the compounding of polyethylene. Whether or not any or all of these are present in a particular sample depends on its proposed application. For instance, if there is concern about oxidation, antioxidants can be added that inhibit the oxidation process.

Storage and service conditions also play a significant role in the lifetime of a polymer. Temperature, chemical environment and sunlight can all have a direct effect on the polymer. Environmental factors, such as contact with solvents and water or an increase in temperature, can accelerate the loss of additives and reduce service life of the polymer. Stresses, much lower than the ultimate tensile strength of a polymer, can also have an effect on the service life of a polymer.

Polyethylene sheathed aluminum wire rope is used on Canadian Forces ships as hand rail. DREA was requested by the Life Cycle Manager (LCMM) to investigate the cracking of

the polyethylene sheathing on a spool of wire rope and identify why it had failed. Discussions with the Riggers Shop, where the wire rope is stored, indicated the wire rope with cracked sheathing had been handled and stored in the same manner as other spools of wire rope. Farther, the sheathing on other spools of wire rope had not cracked. Subsequent to this, the LCMM indicated that the wire rope is rereeled, that is, taken from a large radius reel and wound onto a smaller radius reel, after purchase. The results of the failure investigation are discussed in this report.

Experimental

Materials

Wire rope samples were received from the Riggers Shop, Formation Halifax. Samples of sheathing for analysis were removed from the wire rope prior to analysis.

Differential scanning calorimetry was performed on a DuPont (TA Instruments) Model 2910 DSC. Samples were heated at a rate of 10°C/min from room temperature to 180°C. The melting point was taken as the minimum in the plots of heat flow versus temperature.

Mass crystallinity of the samples was calculated using the total enthalpy method[1],

$$w_c = \frac{\Delta h_f}{\Delta h_{f_o} - \int_{T_i}^{418.5} \left(c_{pa} - c_{pc}\right)dT}$$

where Δh_f is the heat of fusion of the sample and Δh_{f_o} is the heat of fusion for a 100% crystalline polyethylene sample (293 J/g at the equilibrium melting point of 418.5 K), T_i is some arbitrary temperature below the melting range, and c_{pa} and c_{pc} are the specific heats of the amorphous and crystalline components of the sample. Values of c_{pa} and c_{pc} were taken from reference[2]. Setting T_i to 404.0K, and (c_{pa} - c_{pc}) to -0.21cal/deg mole, the adjusted value of Δh_{f_o} was calculated to be 290 J/g. Reported melting points and mass crystallinities for the samples are the average of at least five data points.

Thermogravimetric analysis (TGA) was performed on a DuPont (TA Instruments) model 951 thermogravimetric analyzer. Samples were heated from room temperature to 600°C at a rate of 10°C/min in an inert atmosphere (helium) and then to 800°C in air. First

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derivatives of the weight loss versus temperature curves were taken to determine the temperature of maximum weight loss for the samples.

Gas chromatography/mass spectrometry (GC/MS) analyses were made on a Fisons model 8000 GC/MS (Micromass Canada Ltd.). The mass spectrometer was operated in the scanning mode from 10 to 500 atomic mass units. The GC oven temperature was programmed to hold at 40°C for 5 minutes, then increased at a rate of 10°C/min to 300°C, and then held at 300°C for 9 minutes. Total run time was 40 minutes. Helium was used as the carrier gas.

Samples were pyrolyzed using a CDS model 122 pyroprobe (Chemical Data Systems, Oxford, PA.) using a platinum coil probe and 25mm quartz pyrolysis tubes. The samples were heated at the maximum rate (temperature ramp off) to 700°C using a 20 second interval time.

A Soxhlet extraction apparatus was used to prepare the cable sheathing extracts. A 50/50 (volume/volume) mixture of hexane and acetone was used as the extraction solvent. Extraction time was approximately 16 hours.

Results

Differential Scanning Calorimetry

Typical plots of heat flow versus temperature for samples of cracked and uncracked cable sheathing are shown in Figure 1. The melting point, heat of fusion, and percentage crystallinity of samples of cracked and uncracked polyethylene cable sheathing are shown in Table 1.

Table 1

The melting points, heats of fusion and percentage crystallinity of samples of polyethylene taken from sheathed wire rope samples with and without cracking.

Sample	Melting Point (°C)	Heat of Fusion (J/g)	Percent Crystallinity
cracked	131.0 ± 0.6	191.2 ± 10.1	65.9 ± 3.5
uncracked	129.9 ± 0.6	133.5 ± 7.0	46.0 ± 2.4

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Although the melting points of the cracked and uncracked polyethylene were similar, 131.0°C and 129.9°C respectively, the heats of fusion and therefore the percentage crystallinity of the cracked and uncracked polyethylene were very different. The cracked sample had a heat of fusion of 191.2 J/g which corresponds to approximately 66 % crystallinity while the uncracked sample had a heat of fusion of 133.5 J/g and which corresponds to 46% crystallinity.

Thermogravimetric Analysis

Plots of weight loss versus temperature and the first derivative of weight loss versus temperature for samples of the cracked and uncracked cable sheathing are shown in Figures 2a and 2b respectively. The weight loss versus temperature curves and the temperature of maximum weight loss were similar for the two samples. The cracked sample had a slightly higher residual weight at 600°C than the uncracked sample and a higher residual weight following heating in air to 800°C. However, the differences were small and might be expected for samples of similar types of PE from different suppliers. The differences cannot be used to explain the cracking of one sample of PE and not the other.

Sheathing Extract Analysis

Chromatograms of extracts of the cracked and uncracked cable sheathing are shown in Figure 3. The chromatograms are similar. Butylated hydroxy toluene (19.2 min), hexadecanoic (24.1 min) and octadecanoic acids (26.0 min); dioctylphthalate (29.3 min) and a series of alkenes containing 14 (17.6 min), 16 (20.1 min), 18 (22.3 min), 20 (24.4 min), 22 (26.2 min), 24 (27.9 min) and 26 carbons (29.5 min) were found in both extracts. Butylated hydroxy toluene is a common antioxidant, while hexadecanoic acid and octadecanoic acid are commonly used processing aids[3]. Dioctylphthalate is a plasticizer and the alkenes arise from the synthesis of polyethylene.

The sheathing extract analysis does not indicate that the cracked and uncracked sheathing samples are significantly different with respect to the type or concentration of additives, such as antioxidants or plasticizers.

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Pyrolysis Gas Chromatography/Mass Spectrometry

Pyrograms of samples of the cracked and uncracked cable sheathing are shown in Figures 4a and 4b respectively. The pyrograms of both samples are composed of a series of triplets. These triplets are characteristic of polyethylene[4]. For instance, in Figure 4a there are triplets centered at 10.43 minutes, 12.27 minutes, while Figure 4b has triplets centered at 10.52 minutes, 12.49 minutes. Mass spectral analysis indicated that the compounds giving rise to the peaks in each triplet were a diene, an alkene and an alkane containing the same number of carbons.

However, closer analysis of the pyrolytic degradation products does indicate that there were differences in the two PE sheathing samples. Expanded views of the pyrograms of the two samples are shown in Figure 5. It can be seen that the peaks in the pyrogram of the uncracked sheathing are broader than those in the pyrogram of the cracked sheathing. Also the pyrogram of the uncracked sample has a number of peaks between the triplets. A study[5] of the pyrolysis products of HDPE and LDPE samples found that the LDPE sample produced a number of peaks between the characteristic triplets that were not produced by the HDPE sample. These were attributed to methyl and ethyl substituted alkanes arising from the cleavage of the polymer chain in the vicinity of the branches in the LDPE chain. The presence of pyrolytic degradation compounds between the major triplets in the uncracked PE sheathing sample indicated that it is a LDPE.

Microscopy

A cross section of the PE sheathed wire rope is shown in Figure 6. Side and top views of a crack in the failed polyethylene sheathing are shown in Figures 7a and 7b respectively. The cracks were normal to the long axis of the wire rope and did not progress all the way around the cable perimeter.

A series of electron micrographs of the failure surface are shown in Figures 8 through 13. A low magnification view of the fracture surface of the cable sheathing is shown in Figure 8. The edge of the sheathing that adjoined the aluminum wire rope is at the top of the picture. Visual analysis of the fracture surface indicated that it had dark and light areas. One of the dark areas was located at the outer edge of the cable (area A in Figure 8) while the lighter areas (area B in Figure 8) extended through the thickness of the sheathing to the sheathing/wire rope interface.

Higher magnifications of the dark area (area A in Figure 8) and area outside the dark area (area B in Figure 8) are shown in Figures 9 and 10 respectively. The morphologies of the fracture surfaces in these areas are significantly different. The fracture surface inside the dark area is relatively smooth while the fracture surface outside the dark area has a fibrillar morphology.

The outer edge of the failed sheathing is shown in Figure 11 (area C in Figure 8). A shear lip, characteristic of final failure, can be seen.

Figures 12 shows a higher magnification of the fracture surface in Area B of Figure 8. The fibrillar structure of the polymer at the fracture surface can be seen in this micrograph. This morphology is characteristic of slow crack growth brittle failures in polyethylene[6]. The fracture surface of a polyethylene sample that failed by a slow crack growth brittle fracture mechanism is shown in Figure 13 (page 327 in Reference 6) for comparison.

Discussion

The results of the thermogravimetric and sheathing extract analyses indicated that there were small differences between the two sheathing samples. However, the analyses did not identify anything that could be used to explain the cracking of one of the sheathing samples.

The results of the DSC and py-GC/MS analyses are more definitive. DSC indicated that there was a large difference in the percentage crystallinity of the two sheathing samples, 46% for the uncracked sample versus 65% for the cracked sample. The percentage crystallinities are consistent with low density (46% crystallinity) and medium density (65% crystallinity) PE. This is direct evidence of the difference in the structure of the samples.

These differences are confirmed by the py-GC/MS results. The pyrolysis products of the uncracked (lower crystallinity) sample are similar to those that would be expected from LDPE while those of the cracked sample are consistent with the pyrolytic degradation of higher density PE samples.

Scanning electron microscopy indicated that the sheathing failed by a brittle-type slow crack growth mechanism. This behavior takes place at lower stress levels and over longer

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periods of time than a ductile deformation. The stress responsible for the cracking arose from rereeling of the sheathed wire rope. Polyethylene is composed of crystalline lamellae and amorphous intercrystalline regions. The intercrystalline region contains a number of tie molecules, that is, polymer chains that begin and end in adjacent lamellae, polymer chain ends extending from a crystalline lamella into the intercrystalline region, and entangled polymer chains. Under a low load the tie molecules untangle to the point where the load cannot be supported by the remaining tie molecules. The polymer then fails by a brittle manner.

The scanning electron micrographs indicate that the failure initiated away from the outer edge of the sheathing, most likely adjacent to the aluminum wire rope. The crack grew slowly towards the outer edge of the sheathing until the remaining sheathing could not support the load and failed. The shear lip in Figure 12 is an area of final failure.

The sheathing with lower crystallinity did not fail because it has more intercrystalline amorphous region and a greater number of tie molecules. The loads arising from rereeling were not large enough to initiate brittle slow crack growth.

Conclusions

The cracked polyethylene sheathing was made from a higher density PE than the uncracked sheathing. It failed when it was wound onto a cable reel with a smaller diameter than the manufacturer's reel. This introduced stresses that were large enough to initiate brittle slow crack growth in the sheathing. The cracking initiated at the wire rope/sheathing interface. The lower density sheathing, which contained more tie molecules and was less stiff than the high density sheathing, was not subjected to loads high enough to initiate brittle slow crack during the rereeling process.

Cracking of the PE sheathing on wire rope of this type can be eliminated in one of two ways. One is to specify that low density PE is used for the sheathing. Low density PE is less susceptible to brittle slow crack growth than the higher density (more crystalline) PE. Further it is more flexible and lower loads are required to rereel wire rope with this sheathing. The other is to discontinue the practice of rereeling the wire rope. The sheathing will then not be subject to loads that initiate brittle slow crack growth. The rope is used as hand rail and service conditions do not require that the rope be bent at

severe angles. Therefore wire rope sheathed with either the low density or higher density PE should stand up to service conditions.

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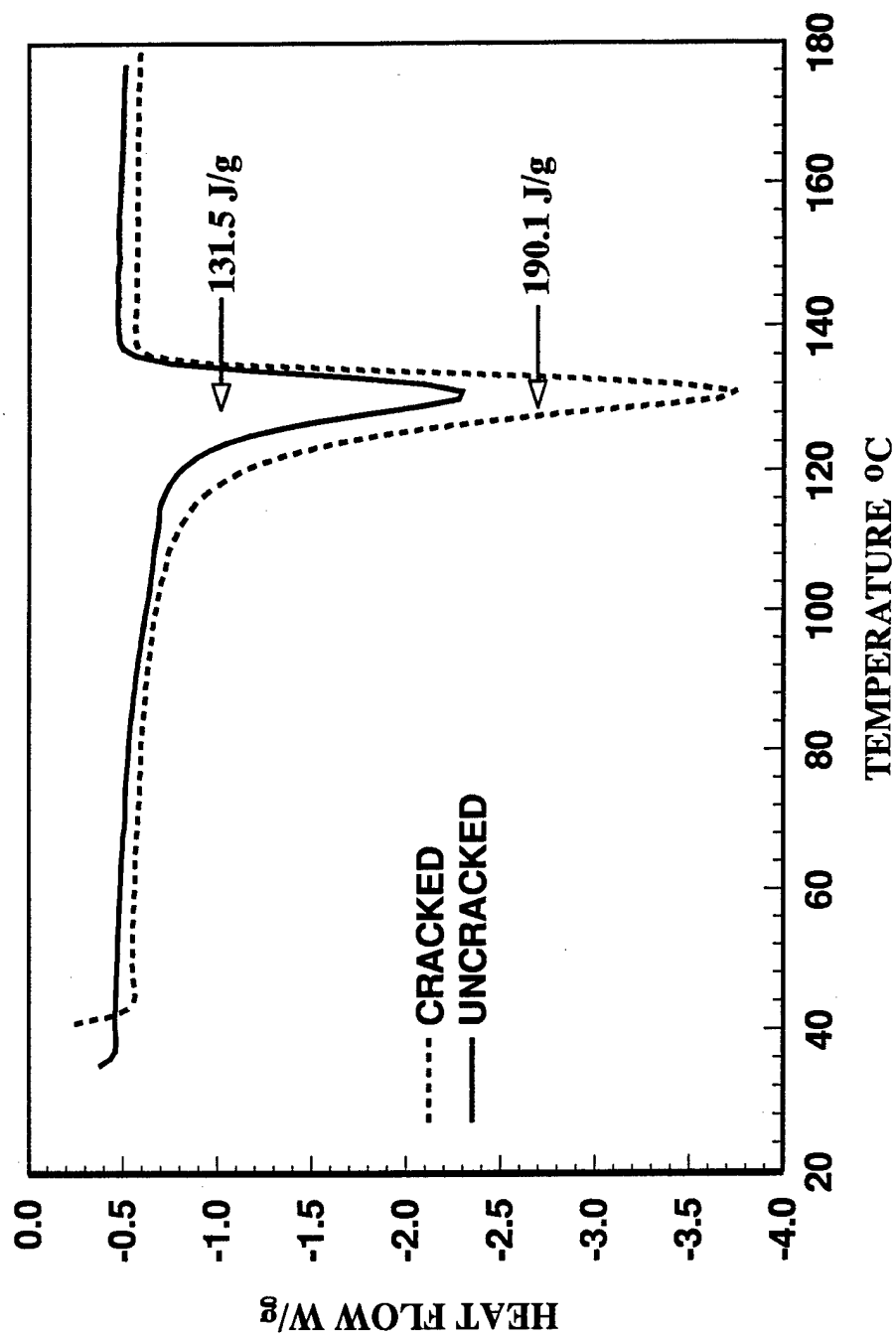
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Figure 1. DSC traces for samples of cracked polyethylene sheathing and uncracked polyethylene sheathing. The traces show heat flow versus temperature for the sample.
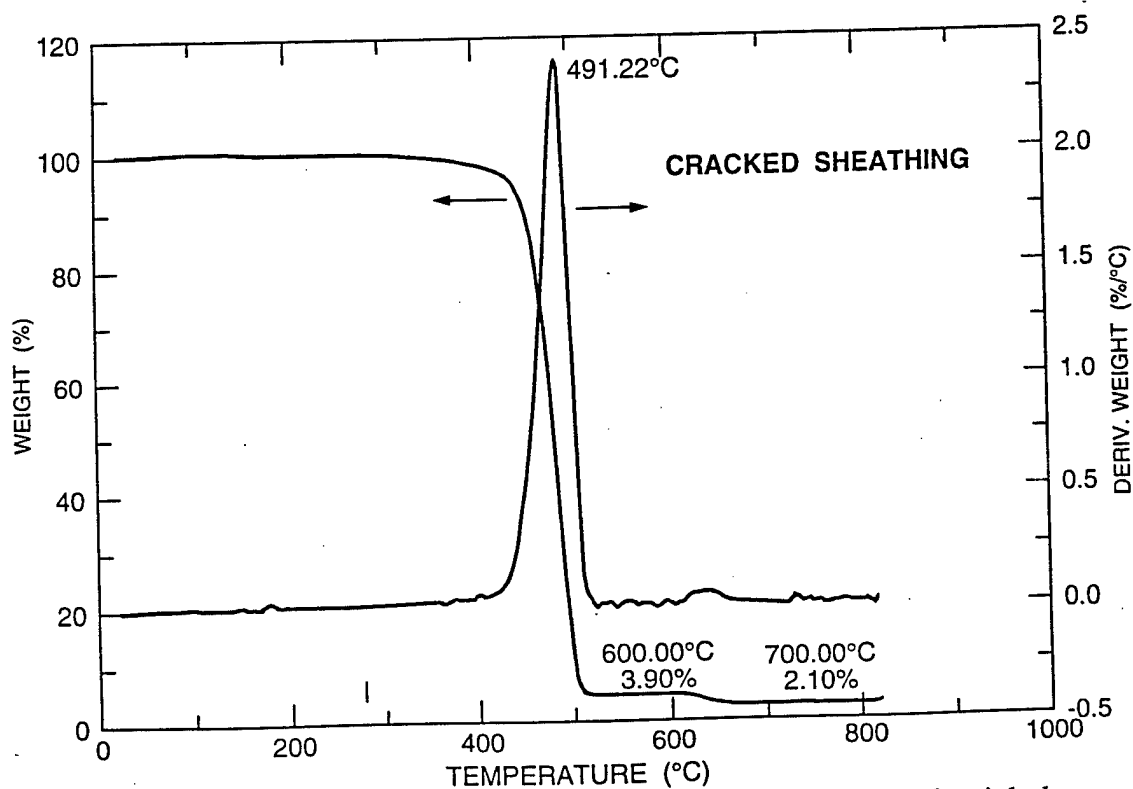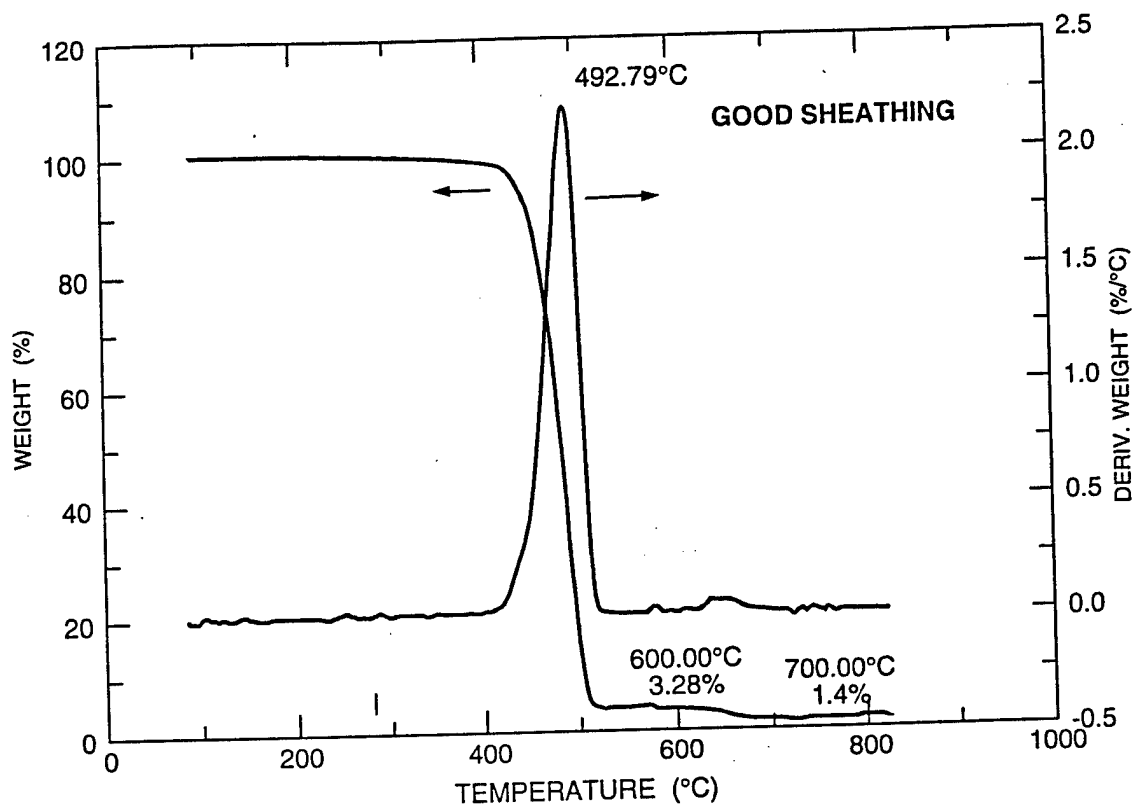
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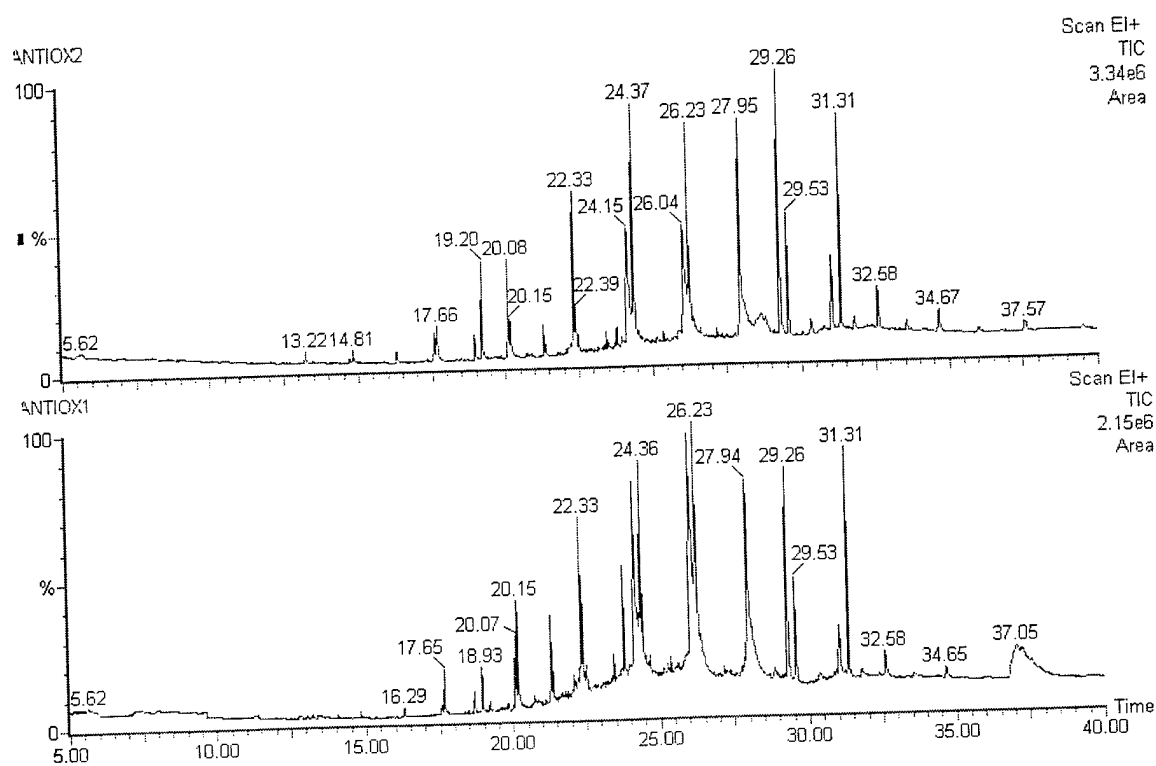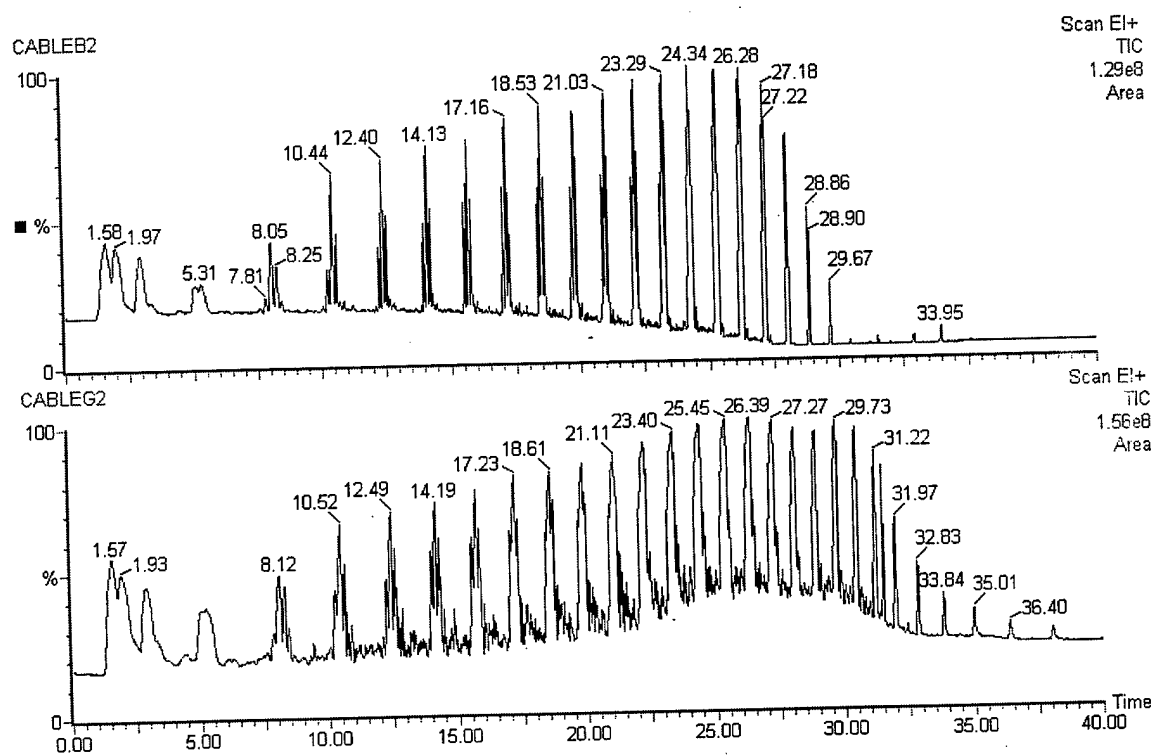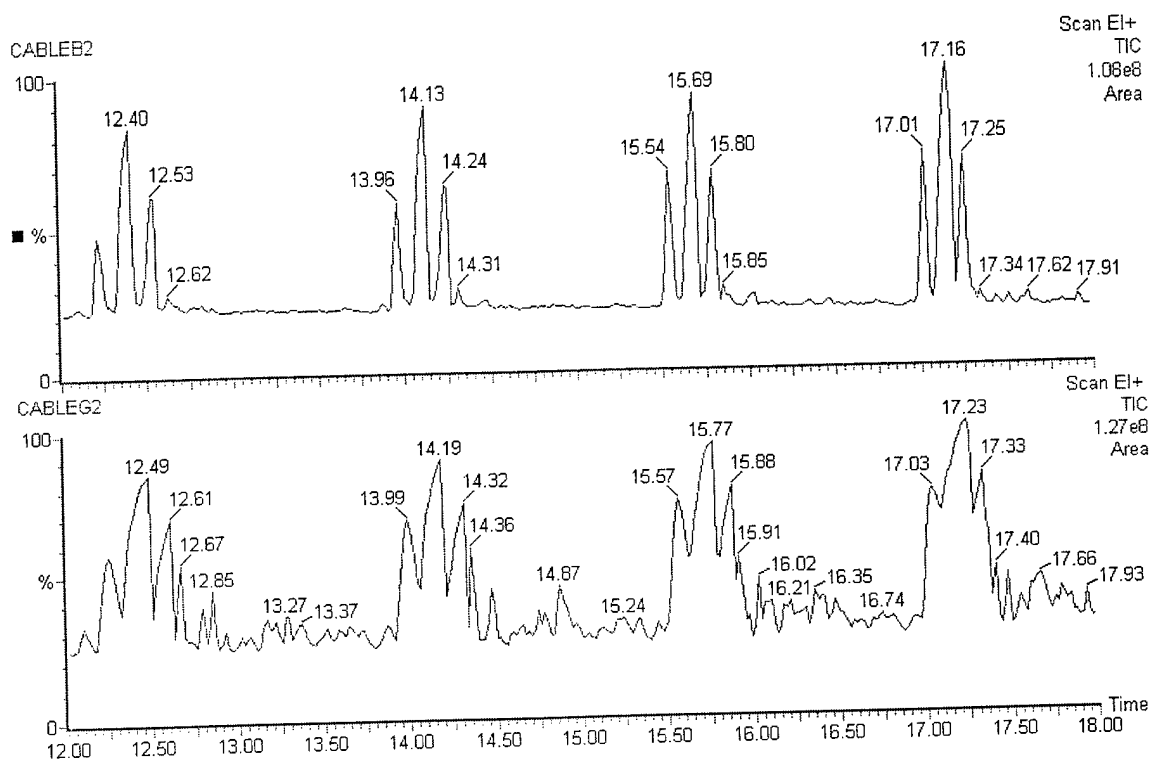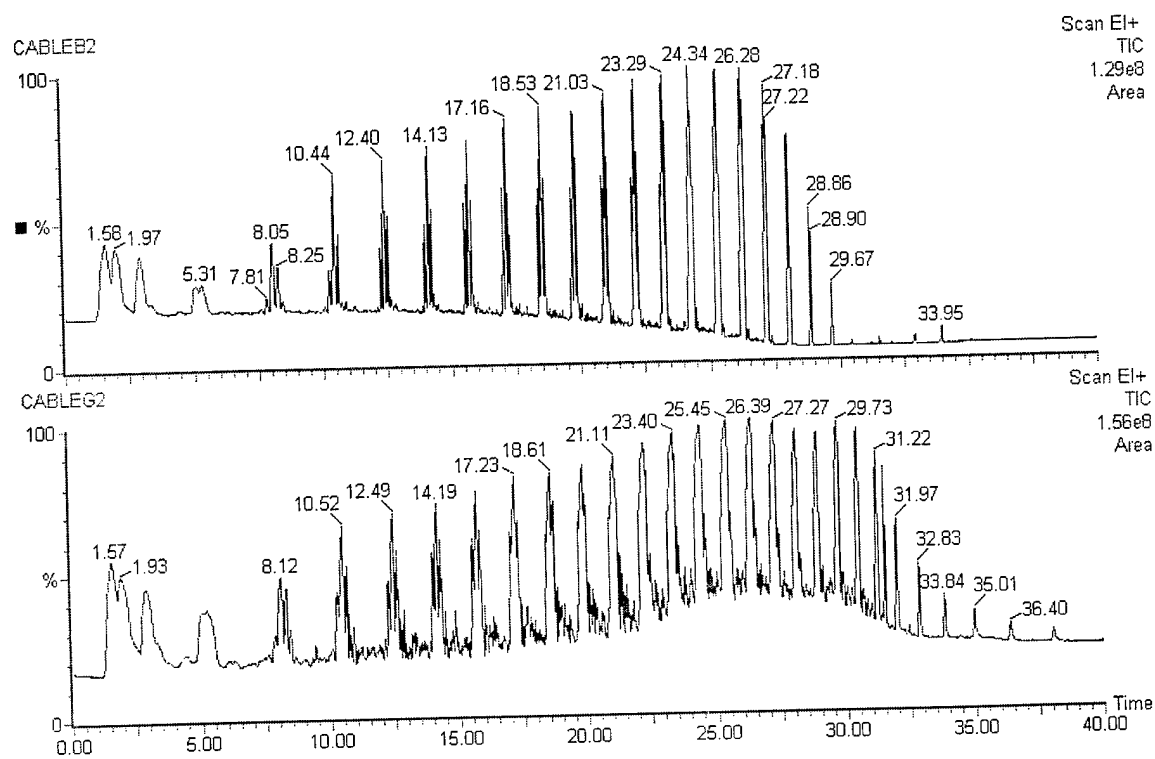
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Figure 3 - Chromatograms of extracts of samples of a) cracked and b) uncracked polyethylene

Figure 4 - Pyrograms of samples of a) cracked and b) uncracked polyethylene sheathing.

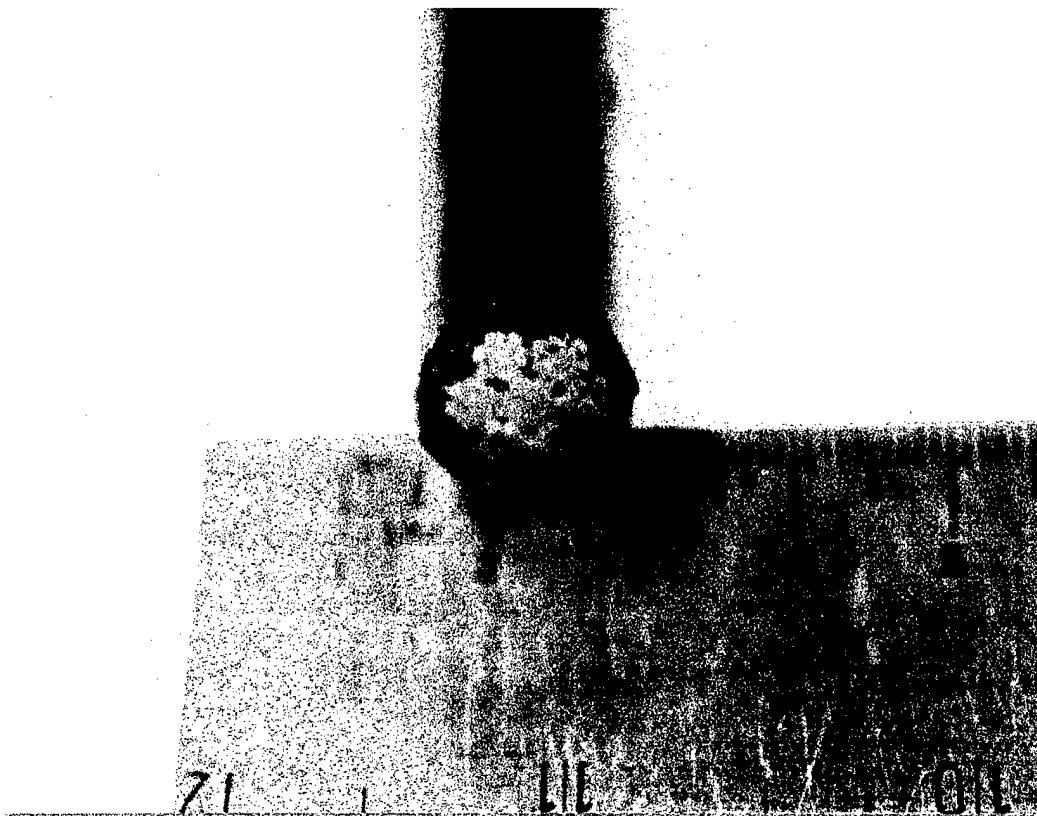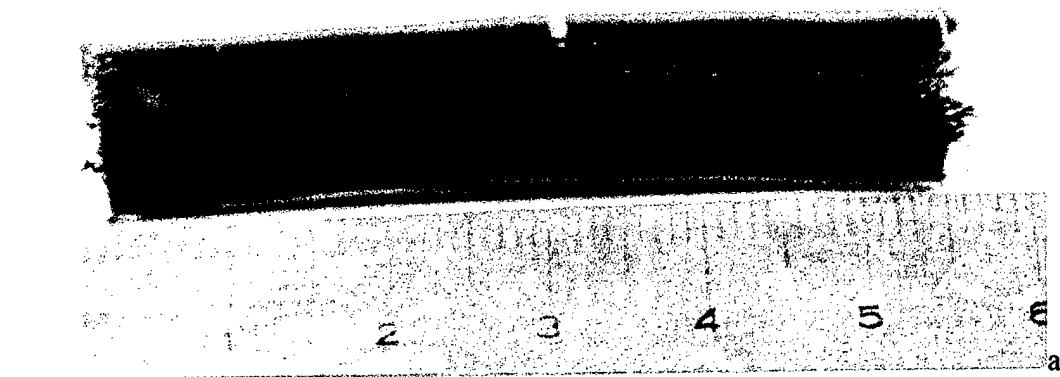Figure 5 - Expanded view of the pyrograms shown in Figure 7 (12 to 18 minutes retention time).

Figure 4 - Pyrograms of samples of a) cracked and b) uncracked polyethylene sheathing.
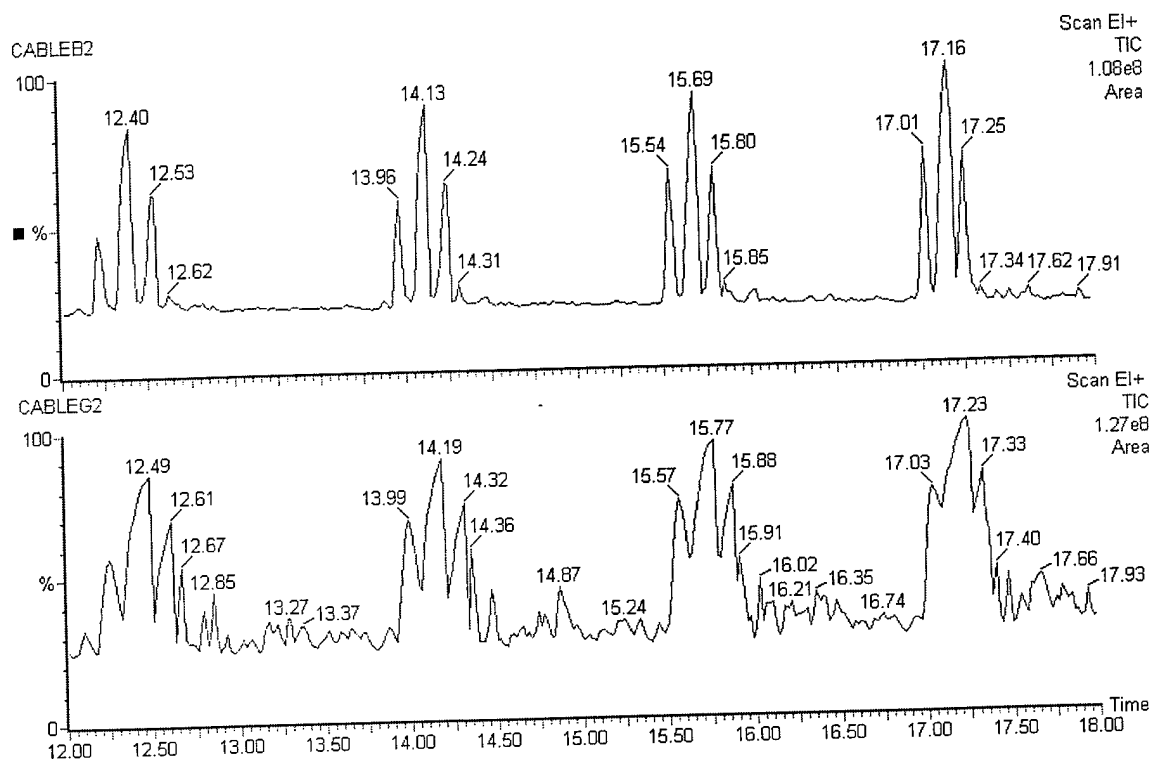
Figure 5 - Expanded view of the pyrograms shown in Figure 7 (12 to 18 minutes retention time).

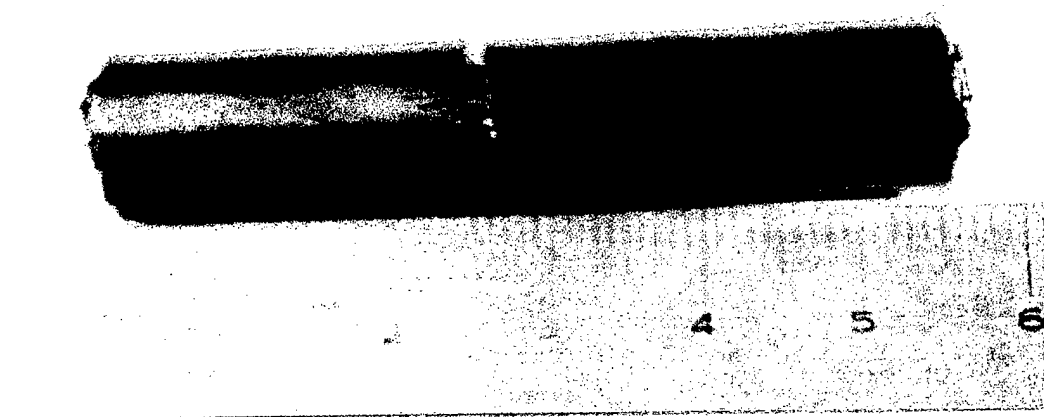Figure 6 - Cross-sectional view of a sample of polyethylene sheathed wire rope.

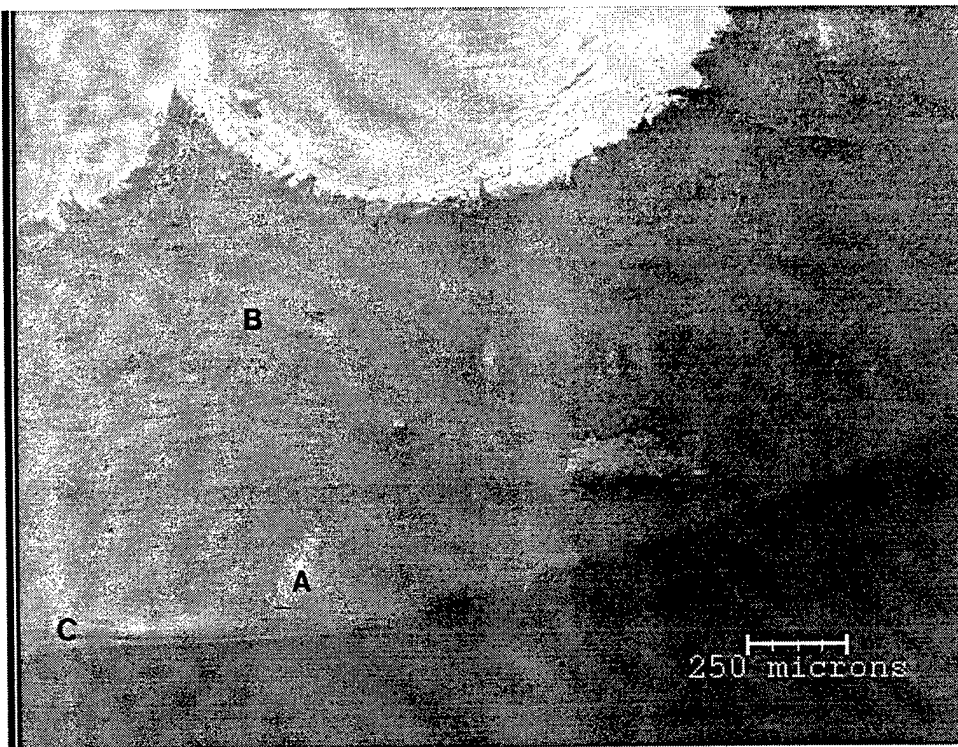Figure 7 - A) Side and b) top views of a crack in a sample of polyethylene sheathed wire rope.

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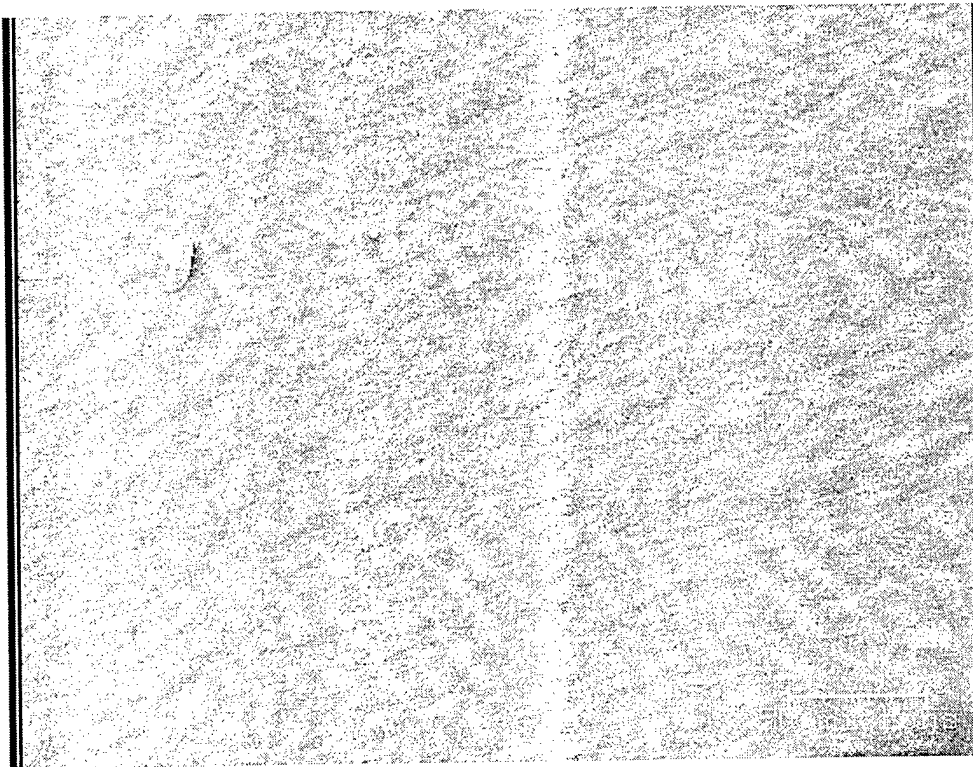
Figure 9 - Higher magnification view of area A in Figure 8. Visually this region appeared darker than the remainder of the fracture surface. Notice how smooth this area is compared to the fracture surface in Figure 10.

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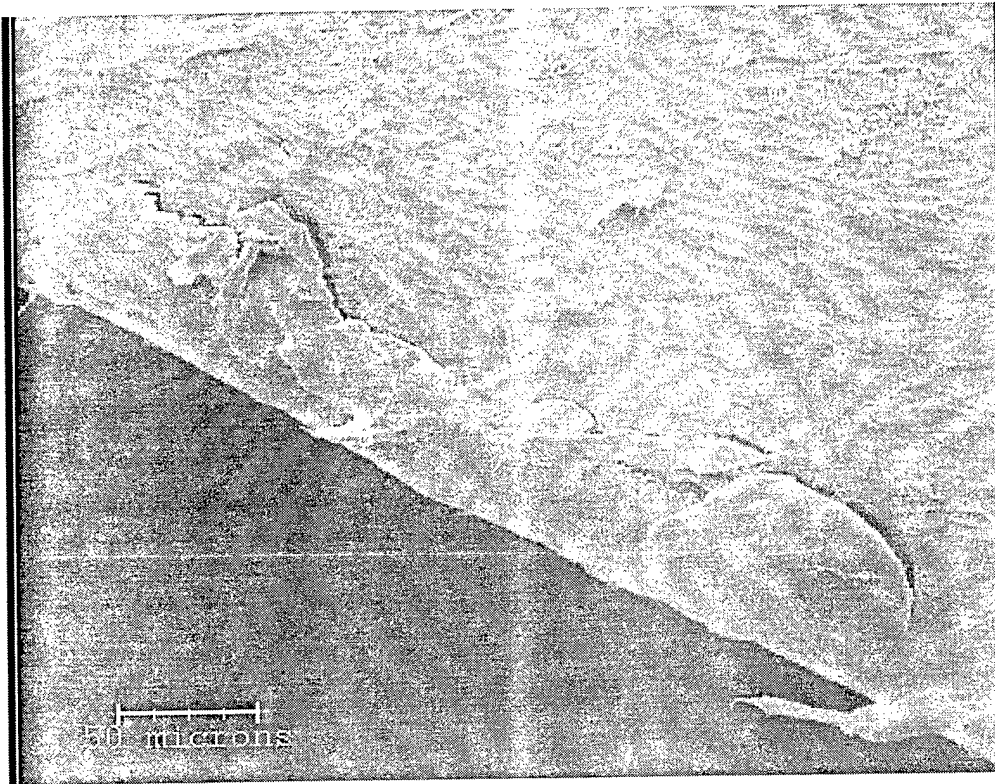
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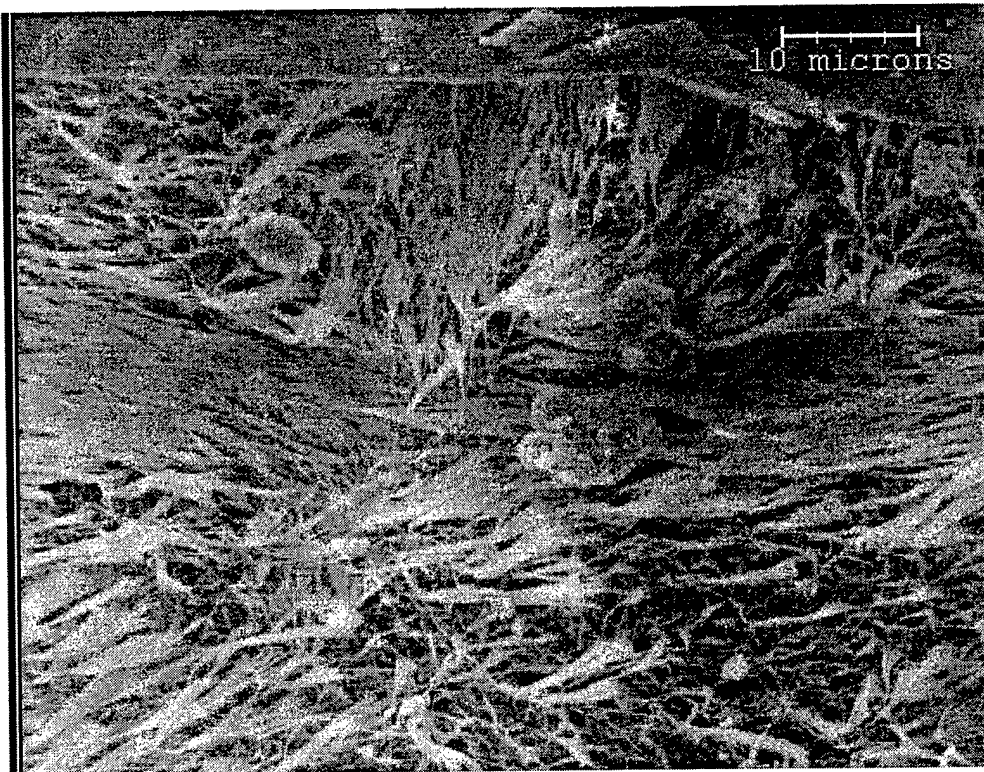
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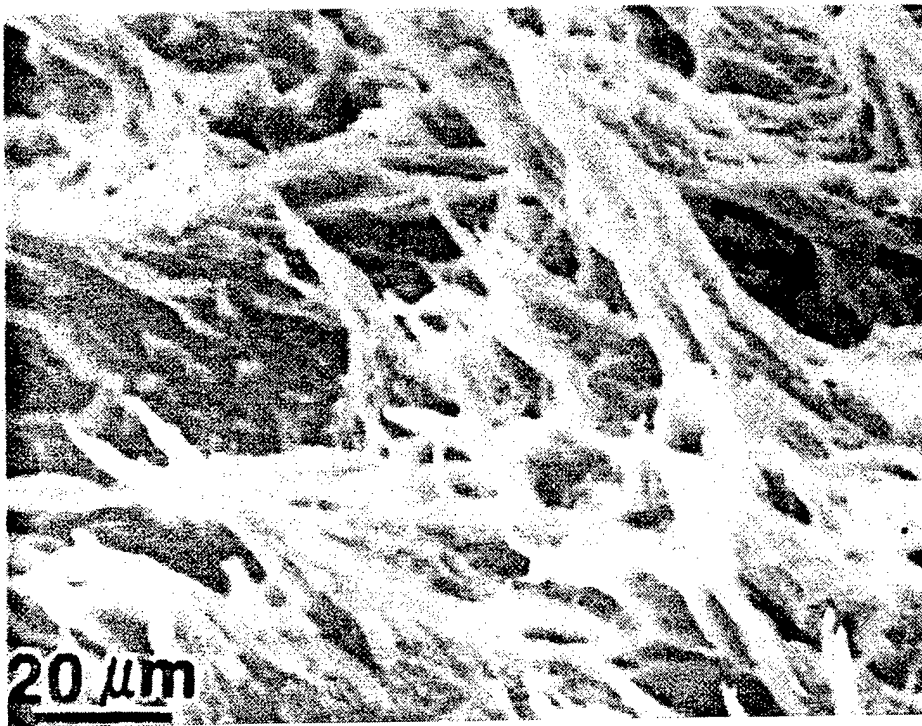
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The results of an investigation of the cracking of the polyethylene (PE) sheathing on aluminum wire rope used on CF Ships are reported. The cracking had not been observed previously and there was concern that this might be related to a change in material or storage conditions. Thermal analysis techniques, such as differential scanning calorimetry (DSC) and pyrolysis-gas chromatography/mass spectrometry (py-GC/MS) indicated that the failed sheathing was higher density PE than the sheathing that did not crack. Analysis of the fracture surface of the cracked sheathing indicated that it had failed by a brittle slow crack growth mechanism. The failure of the higher density PE was attributed to stresses introduced when the sheathed wire rope was transferred to a reel with a smaller diameter. Although the wire rope with the uncracked sheathing had also been transferred to a reel with a smaller diameter, low density PE is less susceptible to this type of cracking.

14. **KEYWORDS, DESCRIPTORS or IDENTIFIERS** (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title).

Cable sheathing
Failure
Polyethylene
Percentage crystallinity
failure analysis
DSC
Pyrolysis gas chromatography/mass spectrometry
brittle slow crack growth